"Tell me that you have found no sign of
New Physics again, I dare you.
I double dare you. Tell me
one more goddamn time!"

# Physics Potential Studies - News

*Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)*

Oviedo, 10/2019

- Introduction & Disclaimer
- Electroweak Precision Observables
- SM and BSM Higgs
- BSM Particle Searches
- Conclusions

# 1. Introduction & Disclaimer

Yesterday Marcel asked me to talk about
"Physics Potential Studies - News"

→ discussion on the update of the spanish input for the ESPPU

What will you see?

- some (imho relevant) plots from the ESPPU Briefing Book
- supplemented with some personal thoughts
- supplemented with some plots of my own

You may become aware of "my personal favorite" ;-)

- mixture of physics and political/money issues
- here only physics
- politics/money/best survival of the field is also important!

## 2. Electroweak Precision Observables

$M_W$ (best from threshold scan)

$$\sigma^0_{\text{had}} = \sum_q \sigma_q(M_Z^2),$$

$$\Gamma_Z = \sum_f \Gamma[Z \to f\bar{f}], \qquad \text{(from a fit to } \sigma_f(s) \text{ at various values of } s)$$

$$R_\ell = \Big[\textstyle\sum_q \sigma_q(M_Z^2)\Big]/\sigma_\ell(M_Z^2), \qquad (\ell = e, \mu, \tau)$$

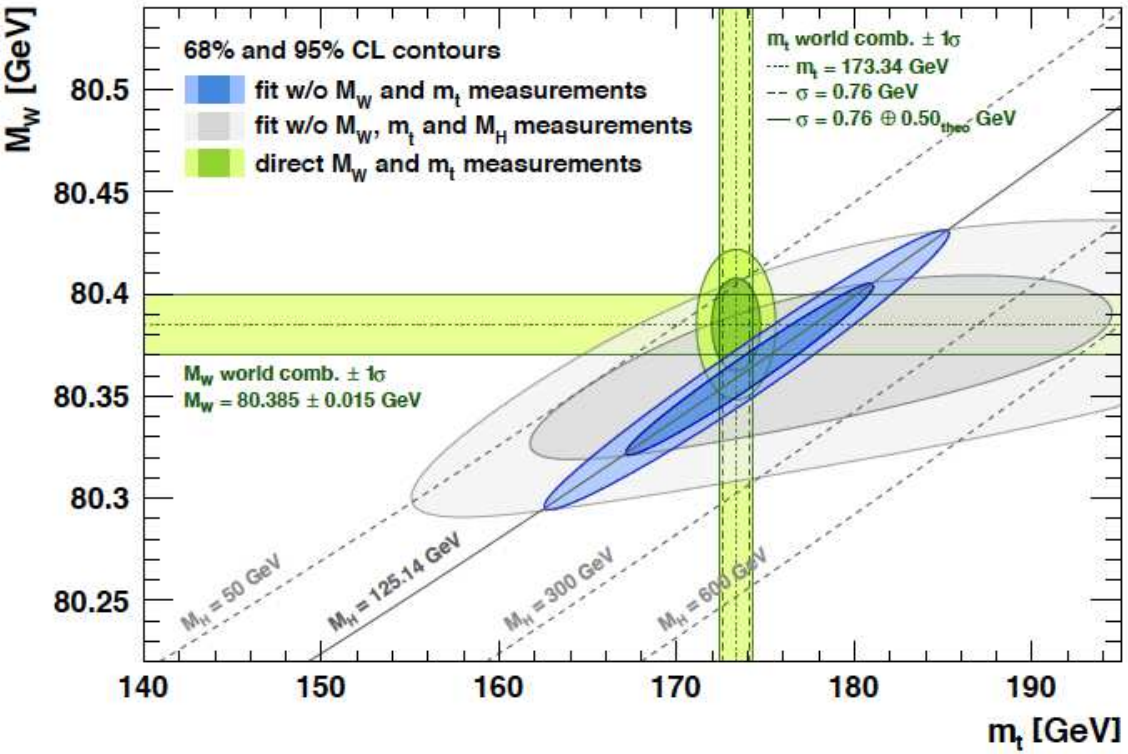
$$R_q = \sigma_q(M_Z^2)/\Big[\textstyle\sum_q \sigma_q(M_Z^2)\Big], \qquad (q = b, c)$$

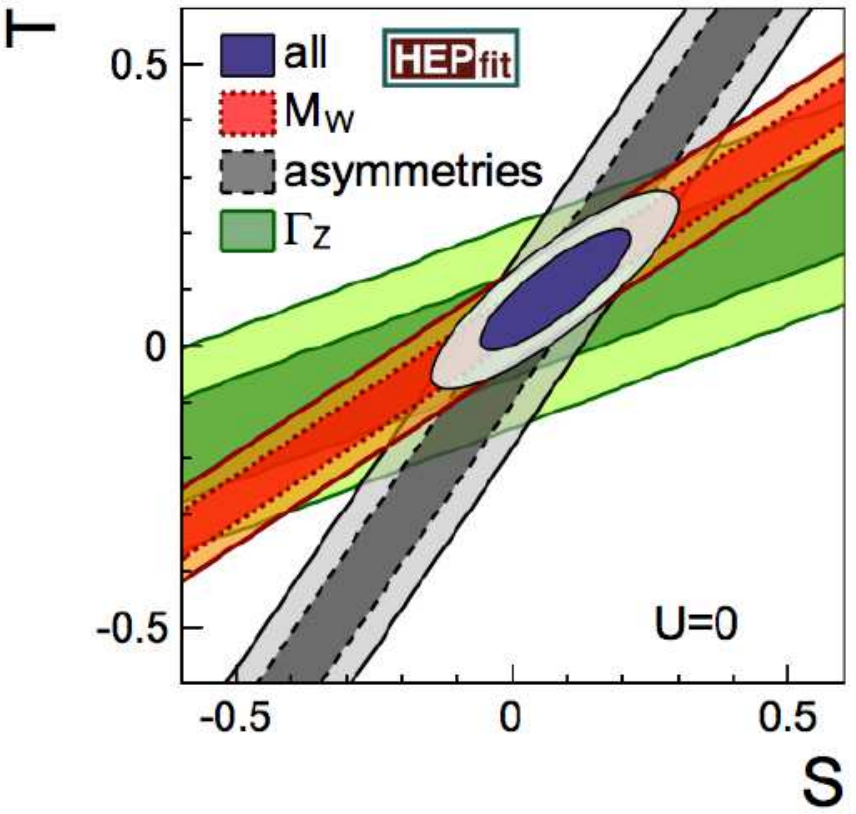
$$A^f_{\text{FB}} = \frac{\sigma_f(\theta < \frac{\pi}{2}) - \sigma_f(\theta > \frac{\pi}{2})}{\sigma_f(\theta < \frac{\pi}{2}) + \sigma_f(\theta > \frac{\pi}{2})} \equiv \tfrac{3}{4}\mathcal{A}_e\mathcal{A}_f,$$

$$A^f_{\text{LR}} = \frac{\sigma_f(P_e < 0) - \sigma_f(P_e > 0)}{\sigma_f(P_e < 0) + \sigma_f(P_e > 0)} \equiv \mathcal{A}_e|P_e|$$

$$\mathcal{A}_f = 2\frac{g_{V_f}/g_{A_f}}{1 + (g_{V_f}/g_{A_f})^2} = \frac{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}}}{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}} + 8(|Q_f|\sin^2\theta^f_{\text{eff}})^2} \quad (f = \ell, b, \ldots)$$

# Status of EWPO



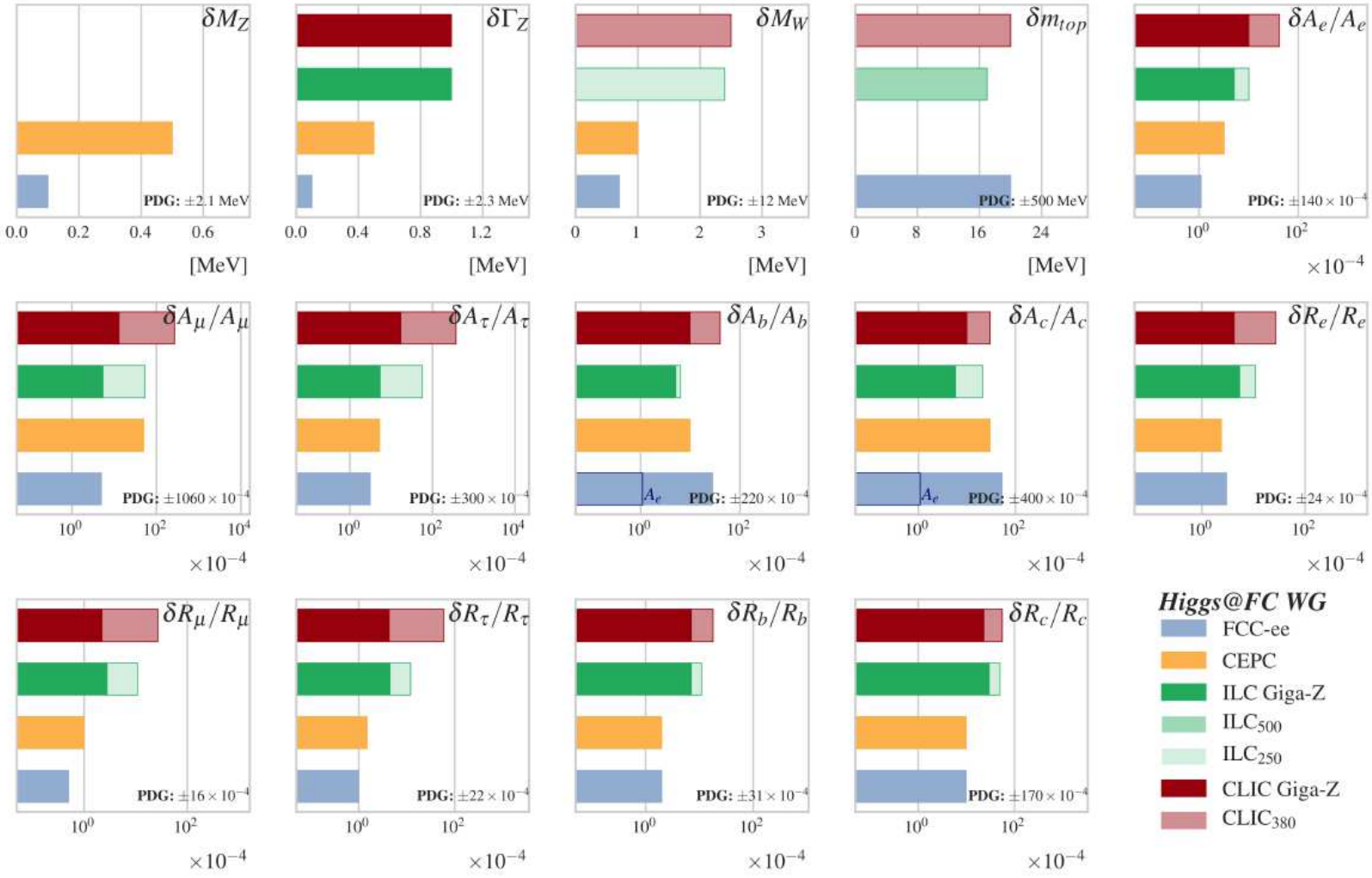




⇒ Indirect limits on $M_H$

⇒ test of the SM at the quantum level

Future: GigaZ/TeraZ, $WW$ running, . . .

# Future expectations for EWPO

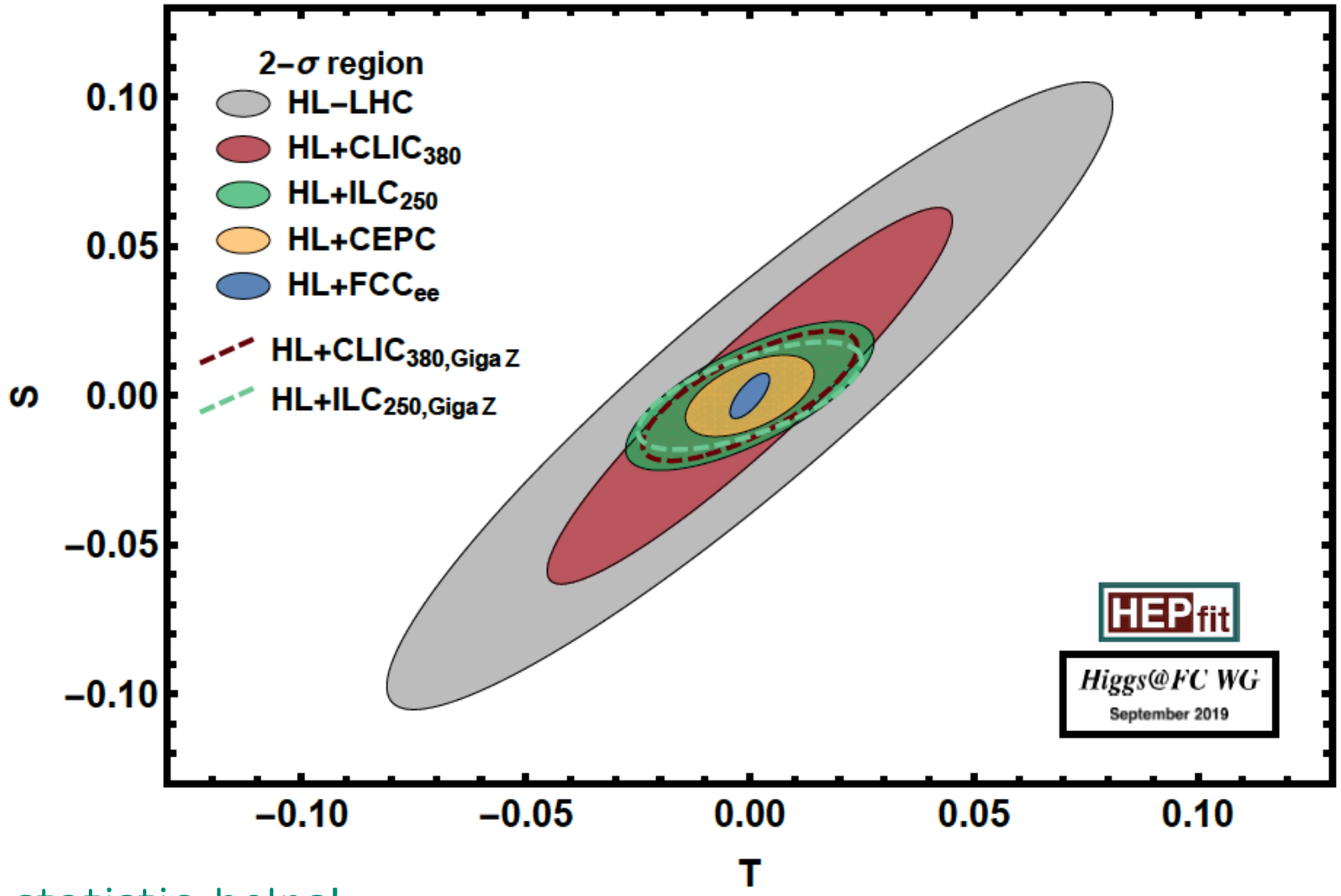



⇒ High statistic helps!

⇒ $ILC_{250}$ similar to ILC-GigaZ

Theory uncertainties?!

## $S$-$T$ future expectations




⇒ High statistic helps!

⇒ $\mathrm{ILC}_{250}$ similar to ILC-GigaZ

Theory uncertainties?!

## Intrinsic uncertainties:

[*A. Freitas, S.H. et al. '19*]

| Quantity | ILC | FCC-ee | Current intrinsic unc. | | Projected unc. |
|---|---|---|---|---|---|
| $M_W$ [MeV] | 3 | 0.5 | 4 | $(\alpha^3, \alpha^2\alpha_s)$ | 1 |
| $\sin^2\theta^\ell_{\text{eff}}$ [$10^{-5}$] | 1.3 | 0.6 | 4.5 | $(\alpha^3, \alpha^2\alpha_s)$ | 1.5 |
| $\Gamma_Z$ [MeV] | 1 | 0.1 | 0.5 | $(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$ | 0.2 (?) |
| $R_b$ [$10^{-5}$] | 15 | 6 | 15 | $(\alpha^3, \alpha^2\alpha_s)$ | 7 (?) |
| $R_l$ [$10^{-3}$] | 10?? | 1 | 5 | $(\alpha^3, \alpha^2\alpha_s)$ | 1.5 (?) |

These calculations are required for the projection:

- complete $\mathcal{O}\left(\alpha\alpha_s^2\right)$ corrections
- fermionic $\mathcal{O}\left(\alpha^2\alpha_s\right)$ corrections
- double-fermionic $\mathcal{O}\left(\alpha^3\right)$ corrections
- leading four-loop corrections enhanced by the top Yukawa coupling
- the $\mathcal{O}\left(\alpha_{\text{bos}}^2\right)$ corrections are done now [*Dubovyka et al. '18*]

For these calculations, qualitatively new developments of existing loop integration techniques will be required, but no conceptual paradigm shift.

$\Rightarrow$ Intrinsic uncertainties can be the limiting factor!

## Summary of future parametric uncertainties:

| Quantity | ILC | FCC-ee | future parametric unc. | Main source |
|---|---|---|---|---|
| $M_W$ [MeV] | $3 \oplus 1$ | $0.5 \oplus 1$ | 1 | $\delta(\Delta\alpha_{\text{had}})$ |
| $\sin^2\theta^{\ell}_{\text{eff}}$ [$10^{-5}$] | 1.3 | 0.6 | 2 | $\delta(\Delta\alpha_{\text{had}})$ |
| $\Gamma_Z$ [MeV] | 1 | 0.1 | 0.5 | |
| $R_b$ [$10^{-5}$] | 15 | 6 | $< 1$ | $\delta\alpha_s$ |

$\Rightarrow$ add quadratic to experimental uncertainties!

$\Rightarrow$ add linearly to intrinsic uncertainties!

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

$\Rightarrow$ Theory uncertainties can be the limiting factor!

## 3. SM and BSM Higgs

$pp$ colliders:

Total width $\Gamma_{H,\text{tot}}$ cannot be measured without further theory assumptions.

$\kappa$'s or couplings only under certain theory assumptions

$e^+e^-$ colliders:

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-$, $\mu^+\mu^-$

$\Rightarrow$ measurement of the Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ indirect measurement of total width

$\Rightarrow$ direct extraction of partial widths (couplings)

Frameworks:

– $\kappa$: many TH assumptions (single resonance, Dirac structure, . . . )

– EFT: less TH assumptions (broader class covered)

## Required precision for Higgs couplings?

MSSM example:

$$\kappa_V \approx 1 - 0.5\% \left(\frac{400\ \text{GeV}}{M_A}\right)^4$$

$$\kappa_t = \kappa_c \approx 1 - \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \approx 1 + \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2$$

Composite Higgs example:

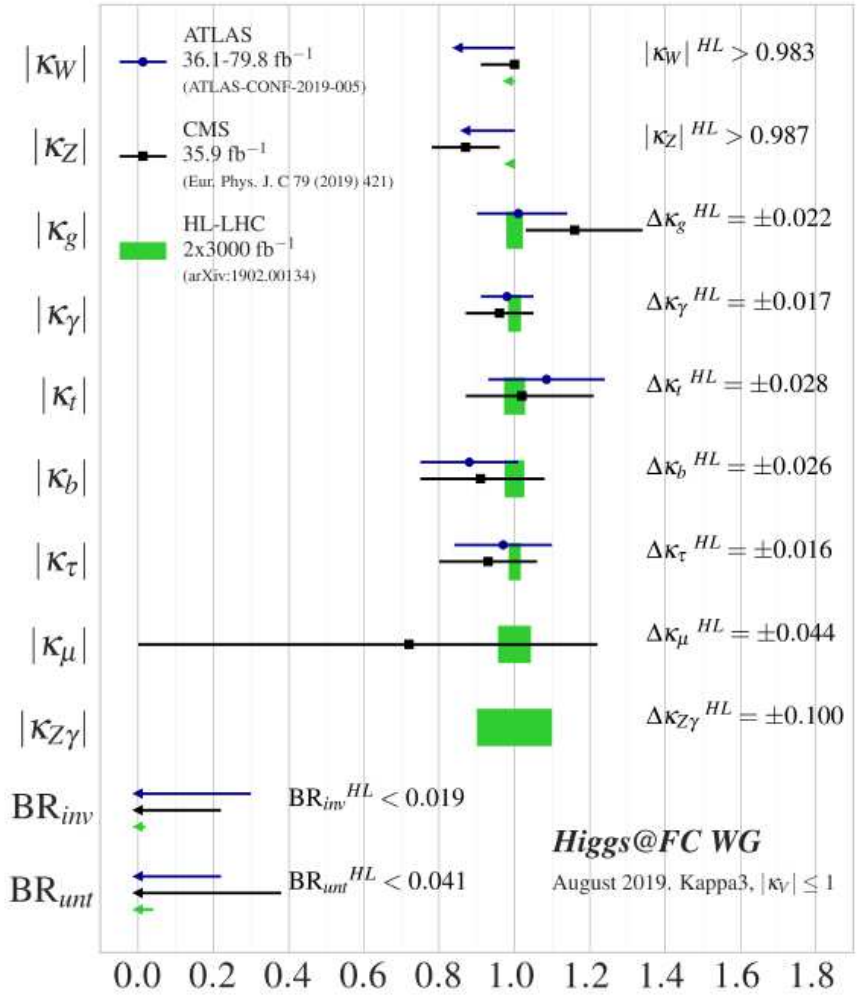
$$\kappa_V \approx 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

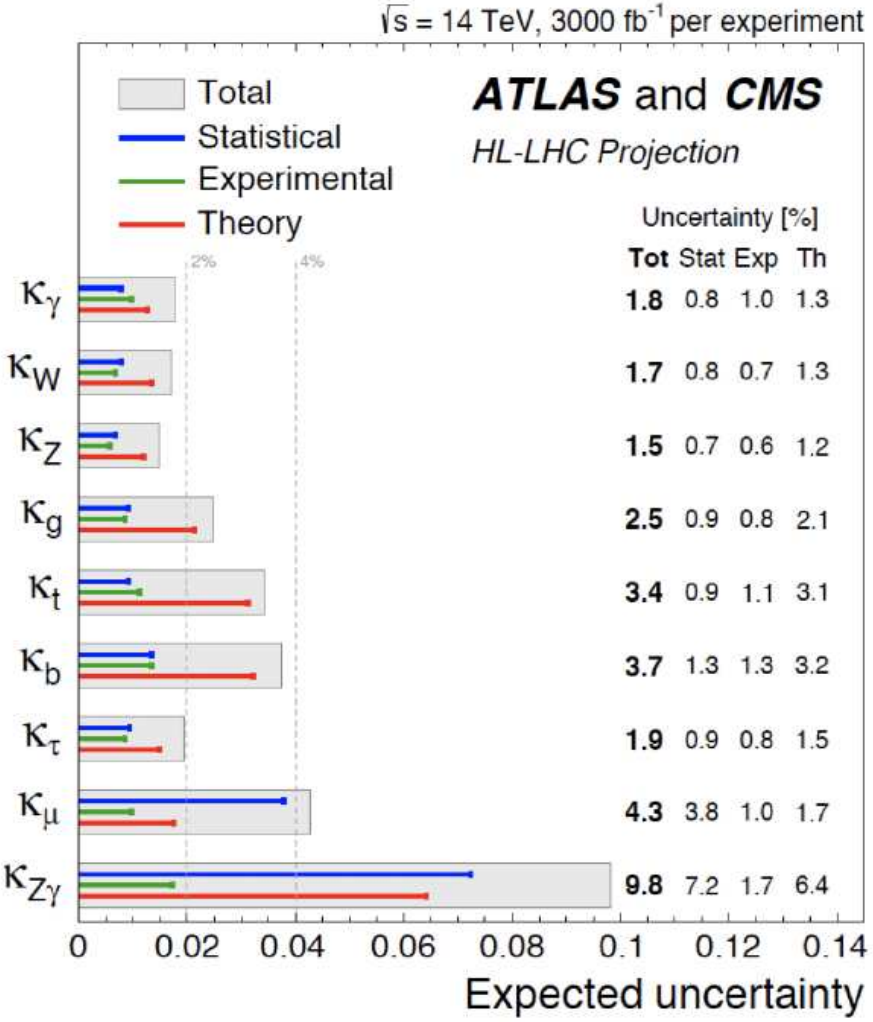
$$\kappa_F \approx 1 - (3-9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

$\Rightarrow$ experimental match?

$\Rightarrow$ theory match?

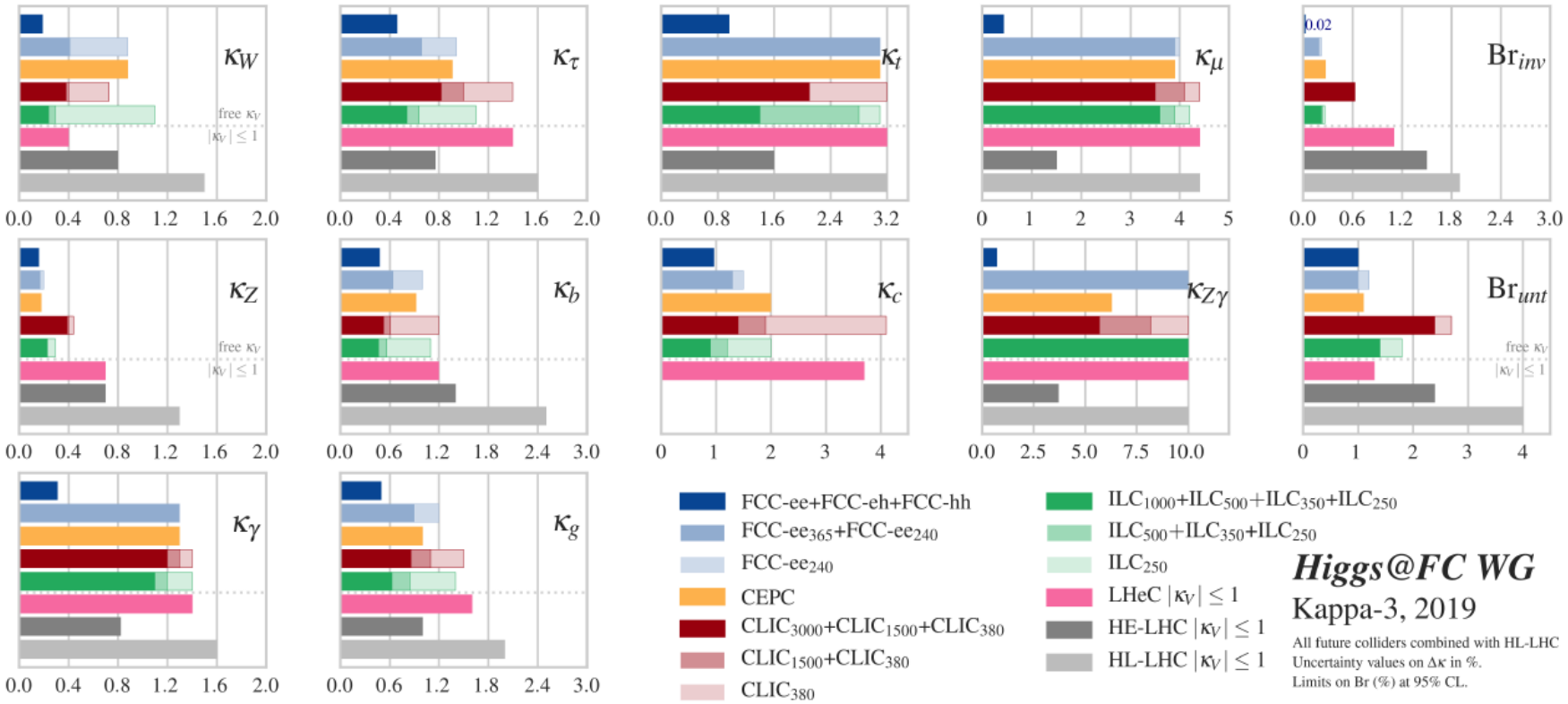
# HL-LHC expectations in $\kappa$-fit




$\Rightarrow$ precision of several percent reachable (theory assumptions)

# Future expectations for $\kappa$ (kappa-3 framework)




$\Rightarrow$ very roughly similar results

$\Rightarrow$ FCC-hh/-he/-ee appears better

$\Rightarrow$ FCC-hh uses different theory assumptions, uncertainties $\lesssim 1\%$

$\Rightarrow$ also remember different time scales!

## Future theory uncertainties? Relevant for "best expectations"?

[*A. Freitas, S.H. et al. '19*]

### Intrinsic uncertainties:

$H \to b\bar{b}, H \to c\bar{c}$: higher-order EW corrections ??

$H \to \tau^+\tau^-, H \to \mu^+\mu^-$: higher-order EW corrections ?

$H \to gg$: improvement difficult

$H \to \gamma\gamma$: already very precise . . .

$H \to Z\gamma$: EW corrections could help . . .

$H \to WW^{(*)}, H \to ZZ^{(*)}$: already very precise, two-loop corrections unclear

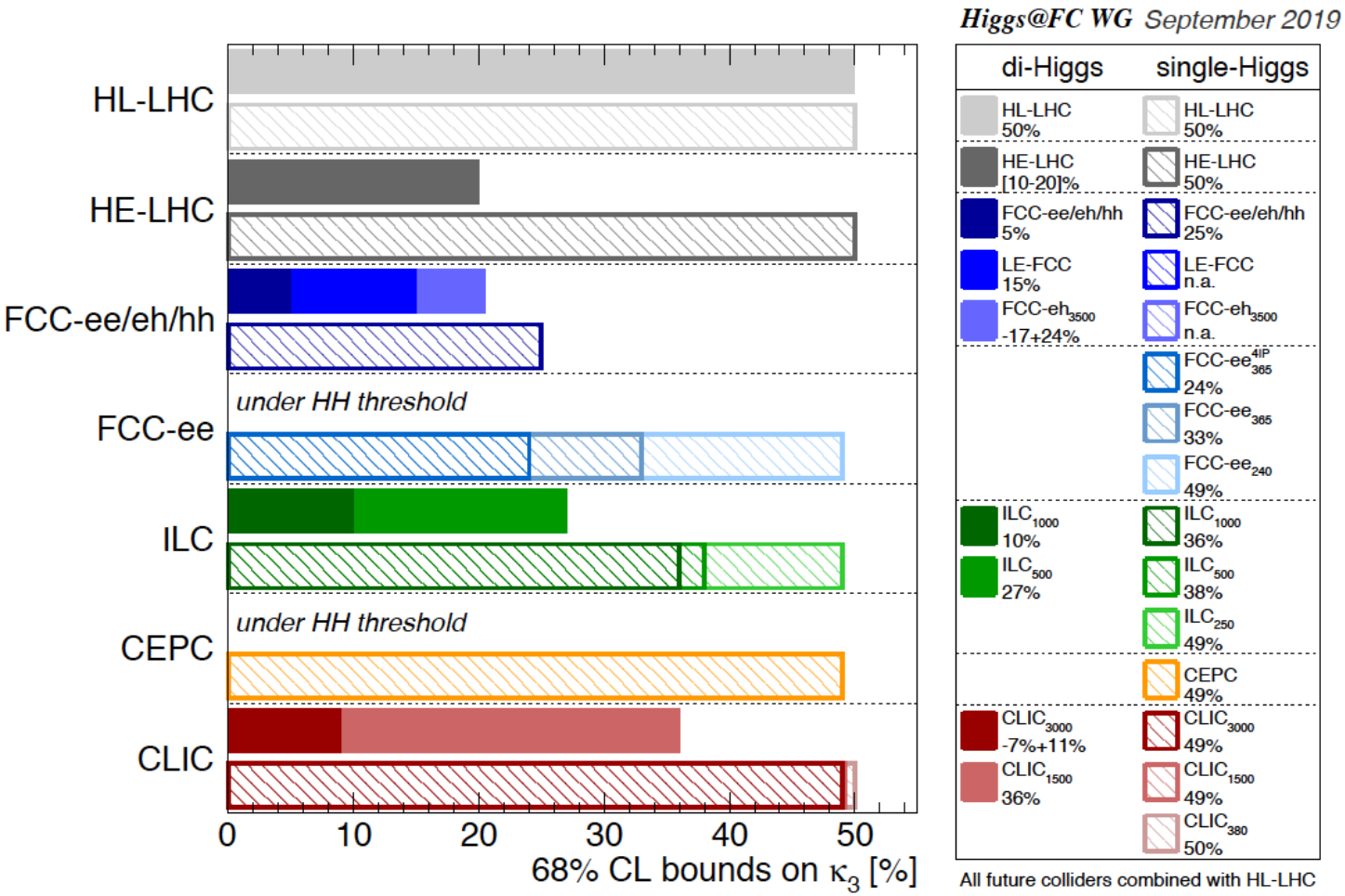
$\Rightarrow$ intrinsic uncertainty can/will be sufficiently under control?!

### Parametric uncertainties:

– largely driven by $\delta m_b \Rightarrow$ improvement unclear (to me)
lattice community does not seem to agree

– some improvement in $\alpha_s$ possible

# The holy grail of Higgs physics: the Higgs self-coupling




$\Rightarrow$ remember intrinsic differences of direct vs. indirect!

$\Rightarrow$ good precision only via direct di-Higgs measurements!

$\Rightarrow$ implications for circular vs. linear . . .

$\Rightarrow$ FCC-hh uses different theory assumptions, uncertainties $\lesssim 1\%$

## What if nature is more complicated than $\kappa$'s?

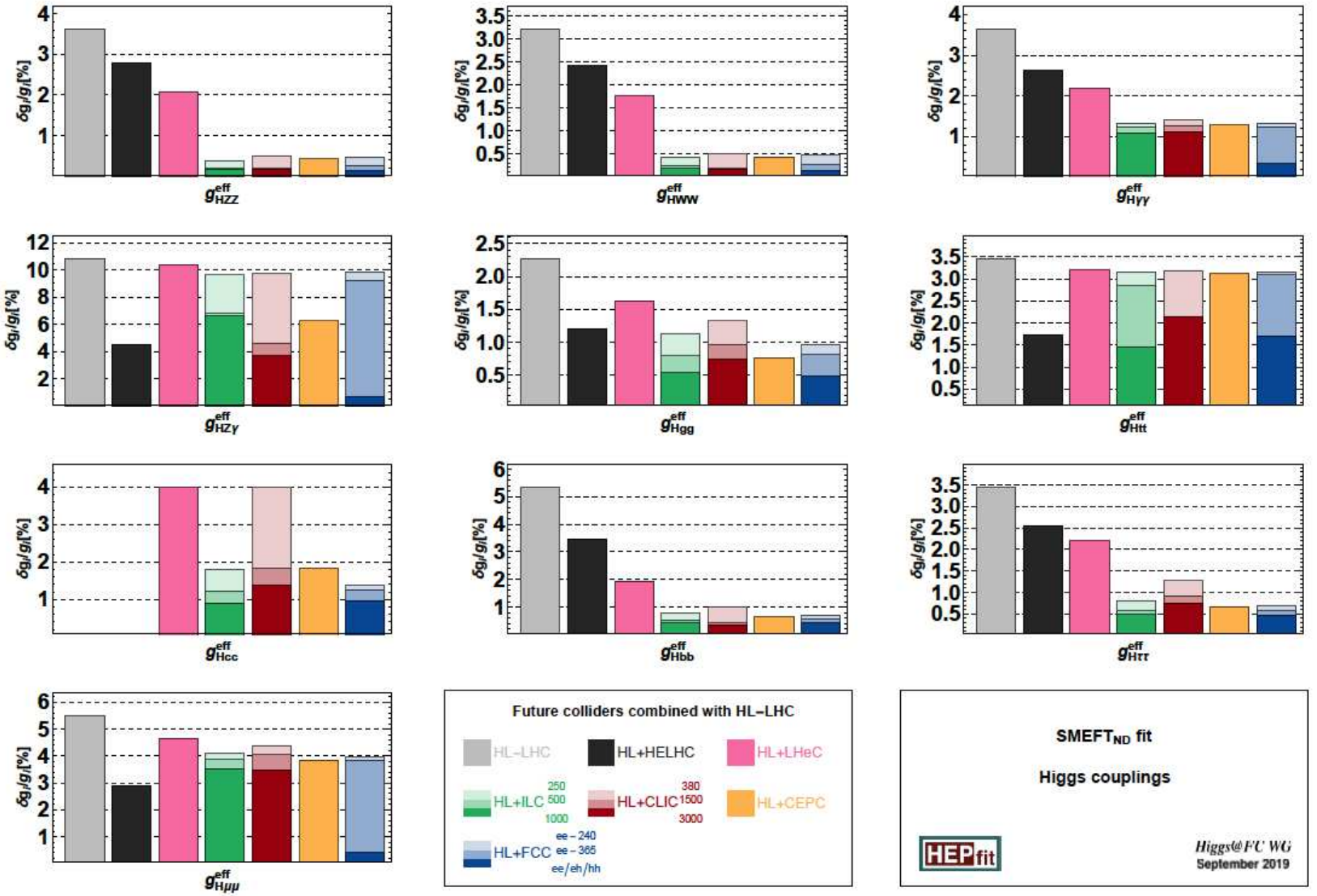
### Assumptions for $\kappa$-framework:

1. Signal corresponds to only one state, no overlapping signal etc.
2. Zero-width approximation
3. Only modification of coupling strength (absolute values of couplings) but not of tensore structure wrt. to SM
4. Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors $\kappa_i$
   ($\kappa_i = 1$ corresponds to the SM case)

Broader class of models covered: EFT
– no light new states
– non-SM-like coupling structures
– UV-complete model: consistent higher-order calculations possible

Note: also EFT does NOT cover all models
$\Rightarrow$ investigate in addition "realistic" models!

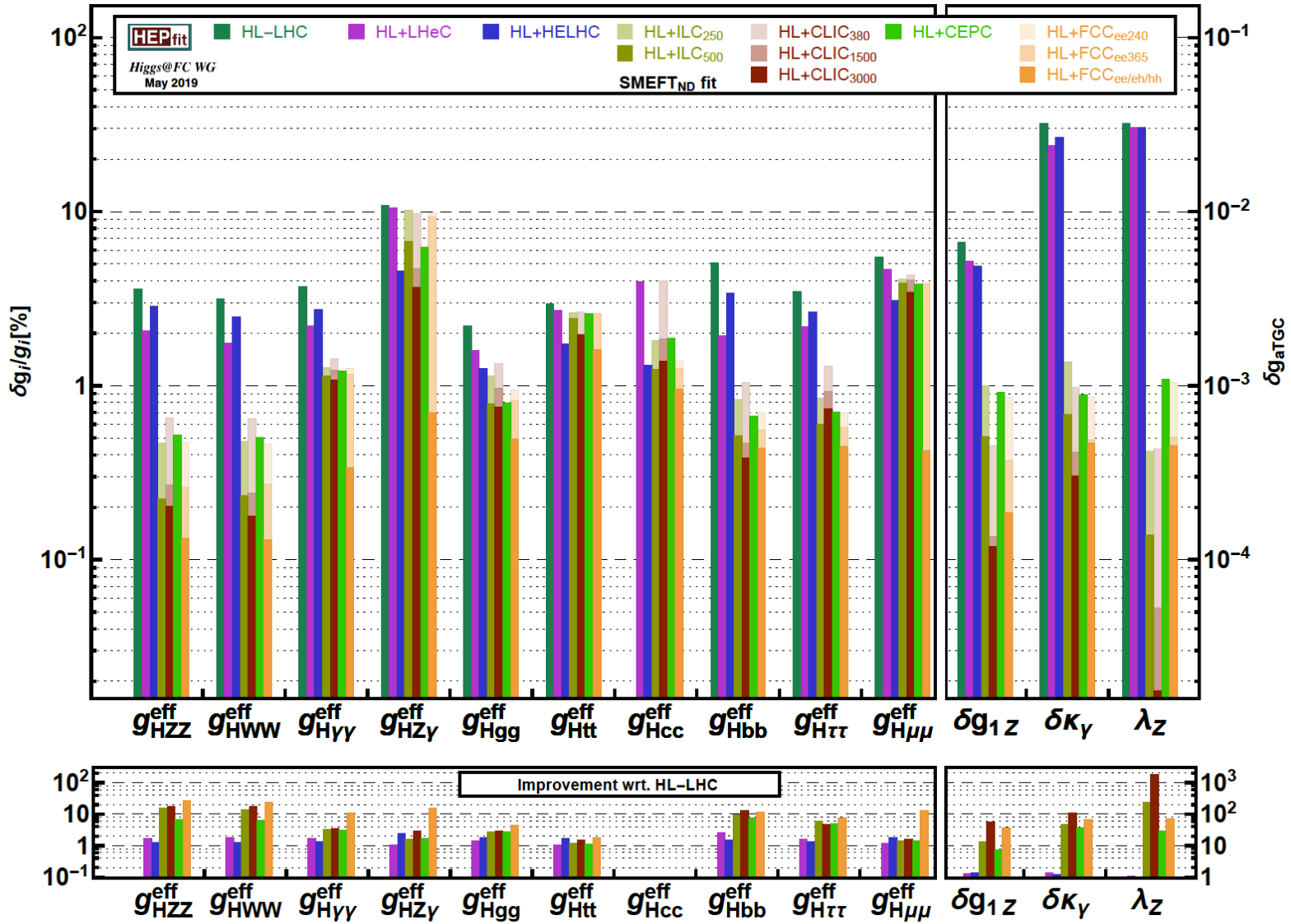
# Future expectations for Higgs couplings in SMEFT (I)




$\Rightarrow$ clear improvement with $e^+e^-$ colliders!

$\Rightarrow$ similar performance (polarization vs. luminosity)

# Future expections for Higgs couplings in SMEFT (II)




⇒ clear improvement with $e^+e^-$ colliders!

⇒ similar performance (polarization vs. luminosity)

## Analysis for the HL-LHC and the ILC in a concrete model

[*H. Bahl, P. Bechtle, S.H., S. Liebler, T. Stefaniak, G. Weiglein '19 – PRELIMINARY*]

### Scenario: MSSM

- new set of benchmark scenarios
- in compliance with all experimental data and latest theory calculations

[*E. Bagnaschi et al. '18*]

### HL-LHC:

- will improve direct search limits
- will improve rate measurements (production $\times$ decay)
  systematic/theory uncertainties: S2 scenario

[*M. Cepeda et al. '19 – YR18*]

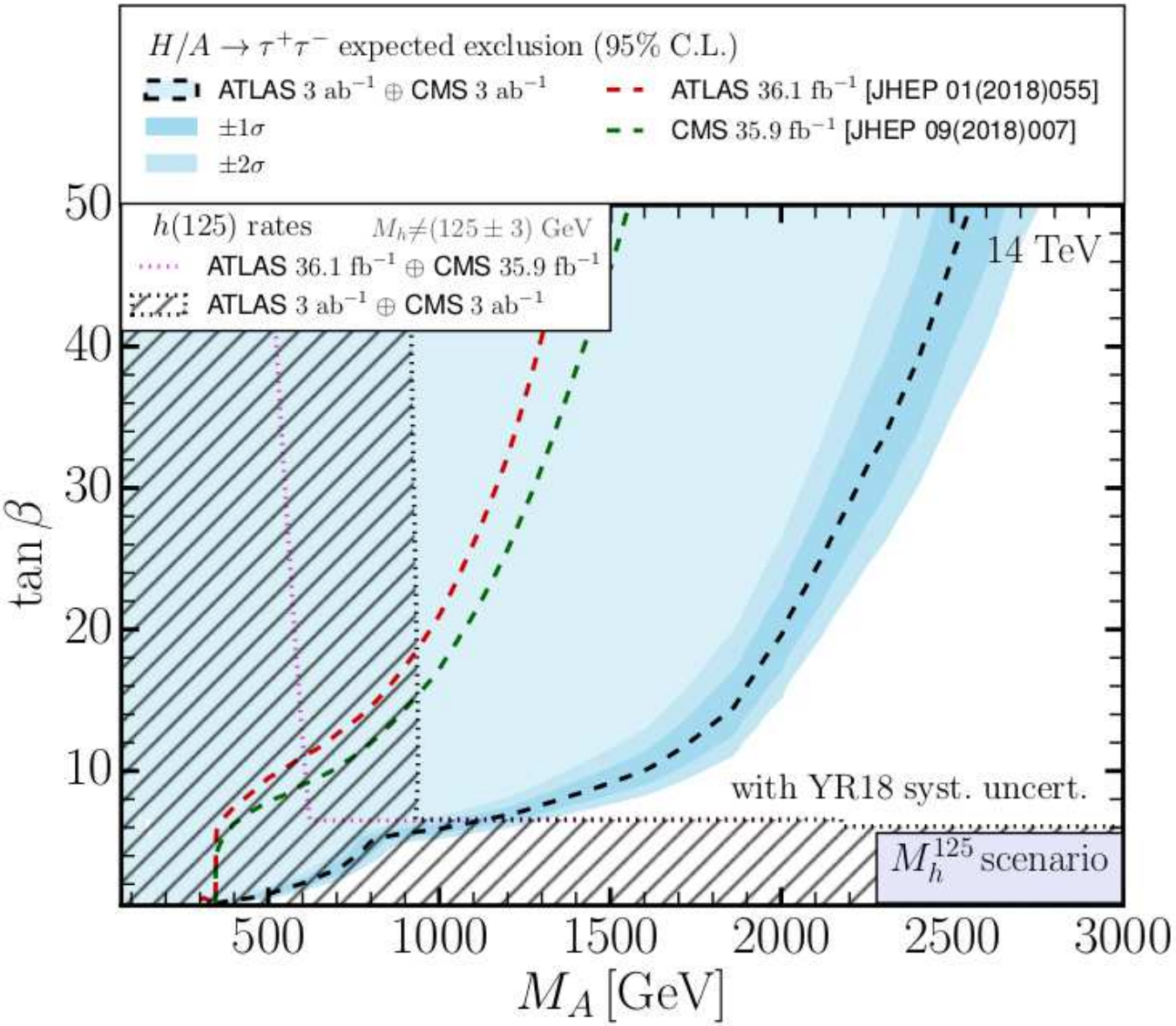
### ILC:

- will improve rate measurements (no theory assumptions!)
  - $250\,\text{fb}^{-1}$ at ILC250 $\oplus$ $500\,\text{fb}^{-1}$ at ILC500
  - polarization: $P(e^-, e^+) = (-80\%, +30\%)$

[*T. Barklow et al. '17, '19*]

# HL-LHC reach in $M_h^{125}$ scenario

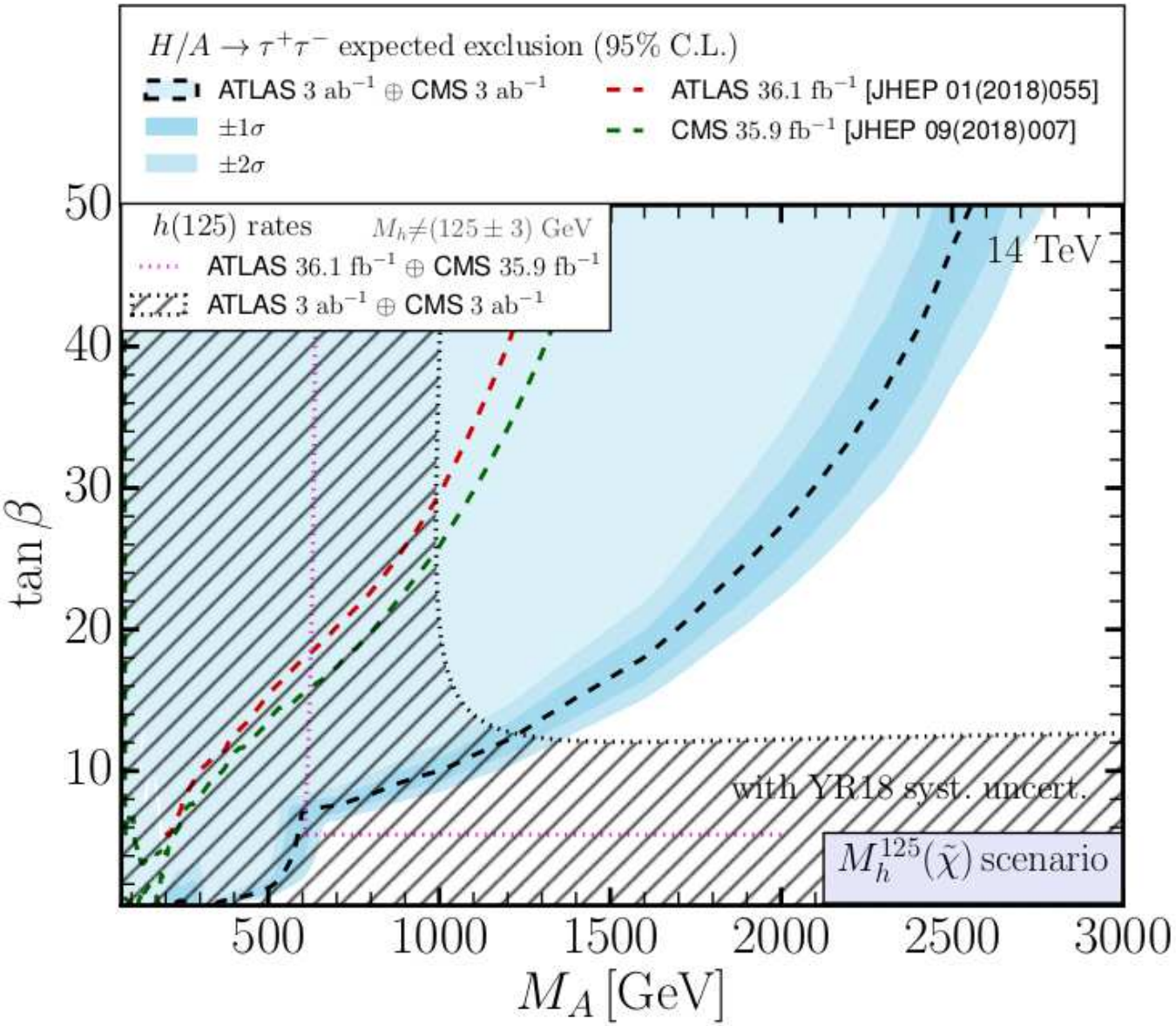
[*H. Bahl et al., PRELIMINARY*]




⇒ direct and indirect measurements: $M_A \gtrsim 1200$ GeV

# HL-LHC reach in $M_h^{125}(\tilde{\chi})$ scenario

[*H. Bahl et al., PRELIMINARY*]

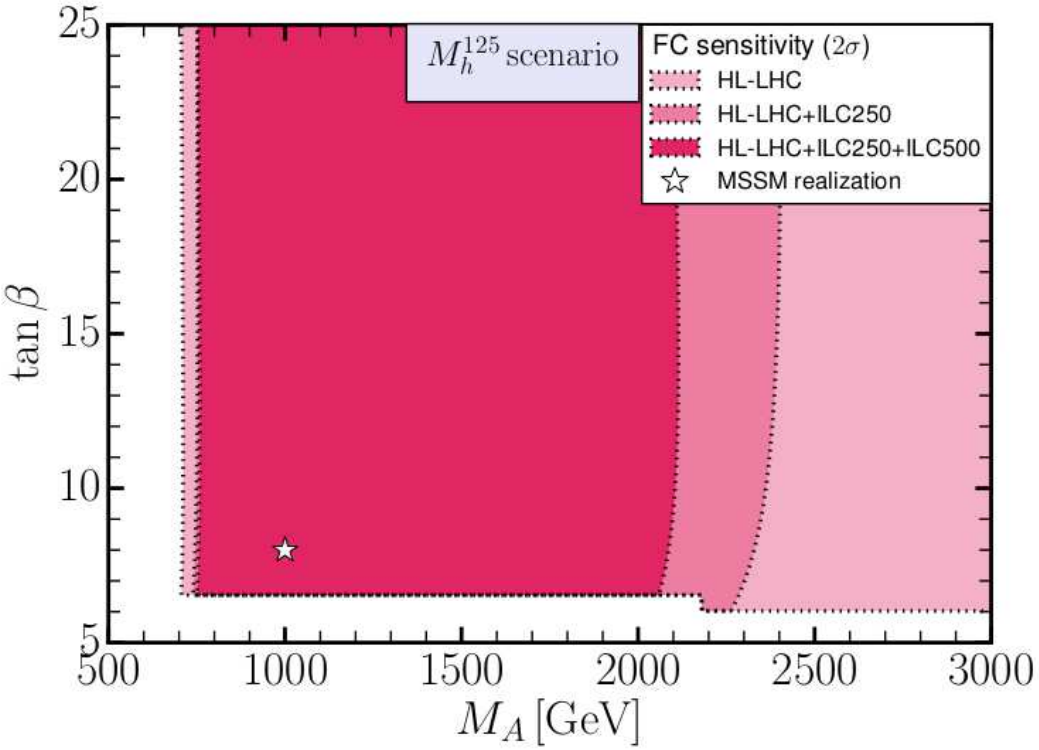


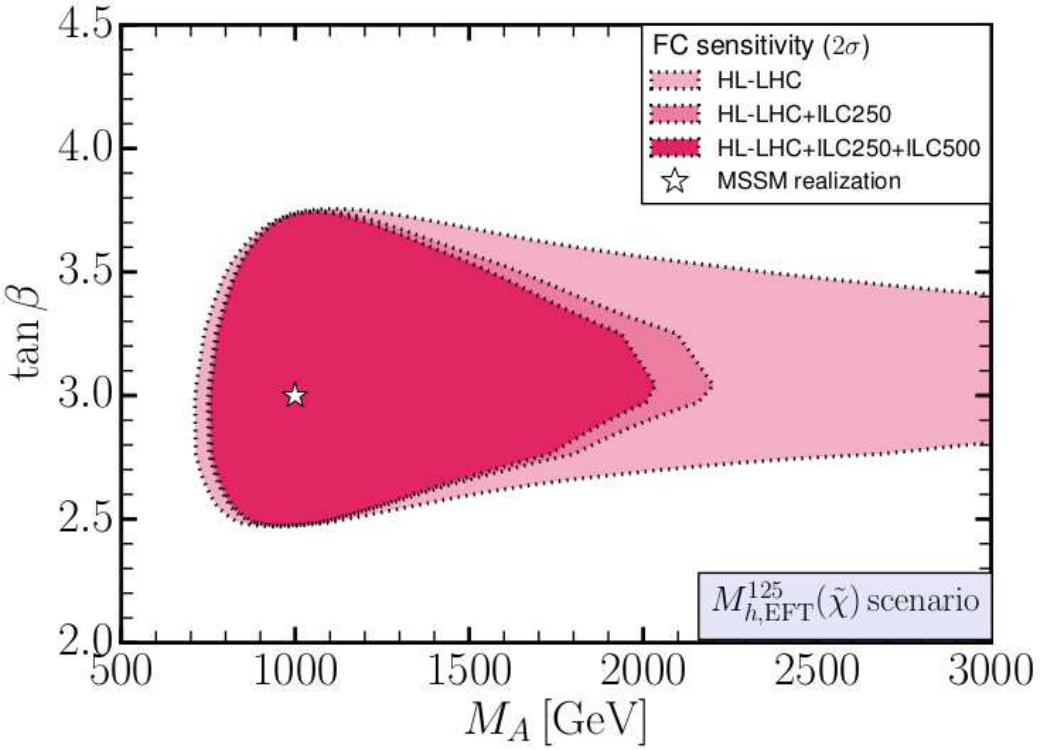

⇒ direct and indirect measurements: $M_A \gtrsim 1200$ GeV

## Relevance of ILC improvement:

[*H. Bahl et al., PRELIMINARY*]

– Assume a realization of an MSSM point: $M_A = 1$ TeV, $\tan\beta = 7/3$
– What limits can be set from rate/coupling measurements?

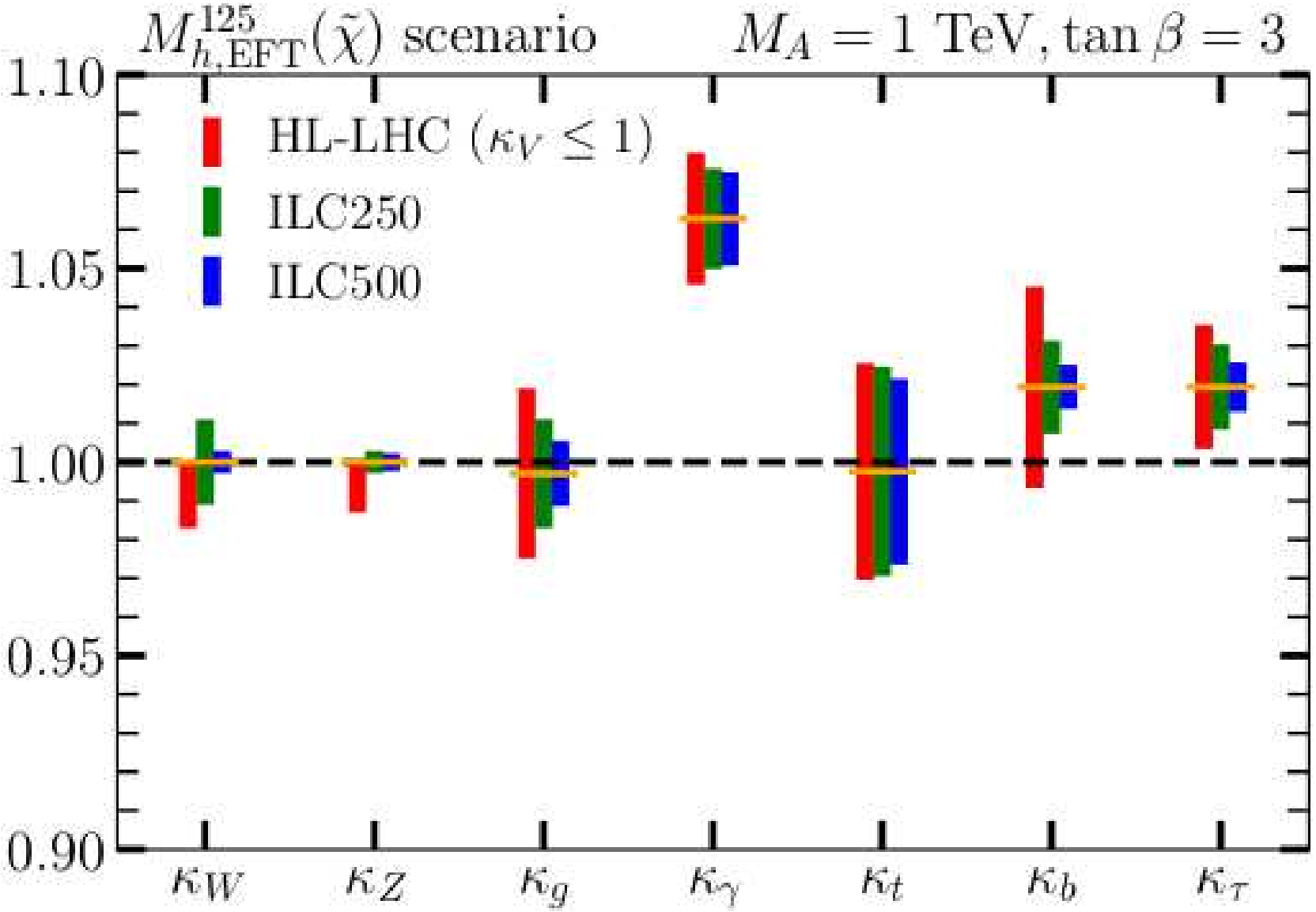



⇒ only ILC measurements give upper limit on $M_A$

⇒ limits on $\tan\beta$ only for small(er) $\tan\beta$

## Individual improvements from ILC in the $\kappa$'s: [*H. Bahl et al., PRELIMINARY*]




$\Rightarrow \geq 2\,\sigma$ deviation are observed, but upper bound only via ILC

# 4. BSM Particle searches

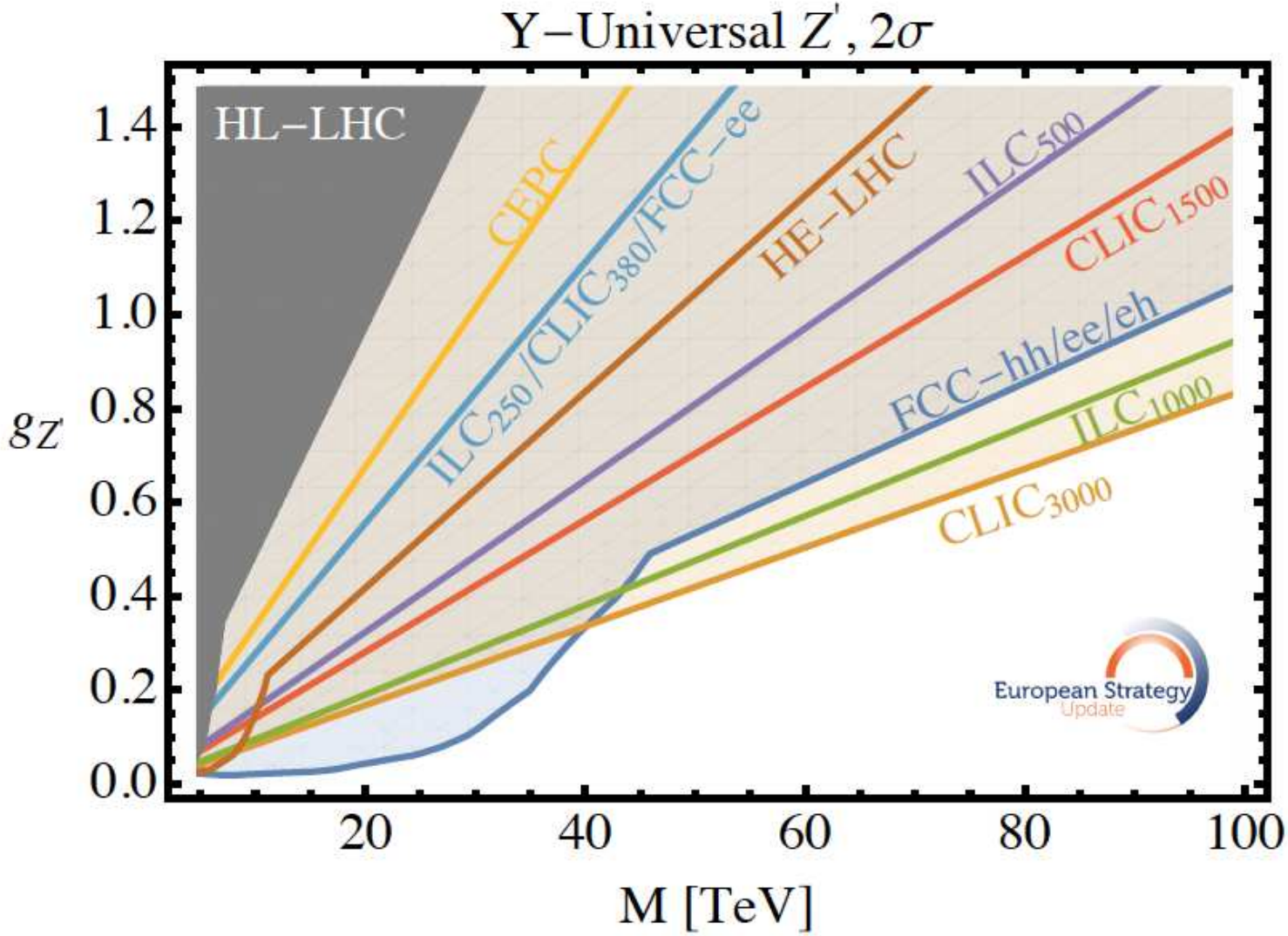
Indirect evidence (deviations from SM expectations) is nice . . .
But we want to see new particles! :-)

$pp$ colliders:
– high reach for colored particles
– problems in "difficult" regions

$e^+e^-$ colliders:
– "easier" reach for uncolored particles
– "difficult" regions better covered

Problem: we do not have a mass scale prediction
$\Rightarrow$ this may change in the near future with $(g-2)_\mu$ from Fermilab!
possible: similar central value, uncertainty reduced
$\Rightarrow$ not too heavy EW particles!

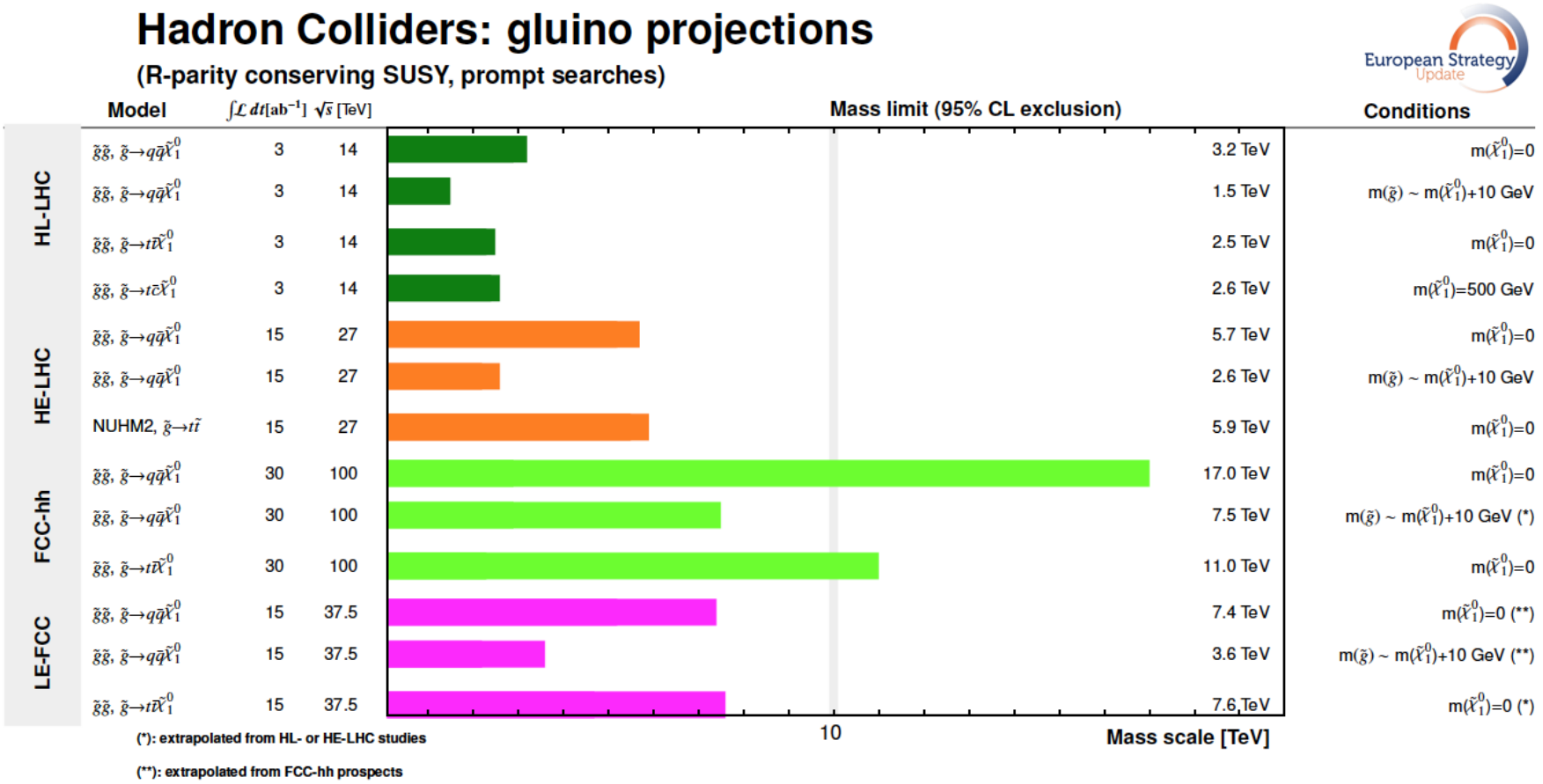
## Future reach in "simplified $Z'$ model"




$\Rightarrow$ impressive indirect reach

$\Rightarrow$ $e^+e^-$ colliders "win"

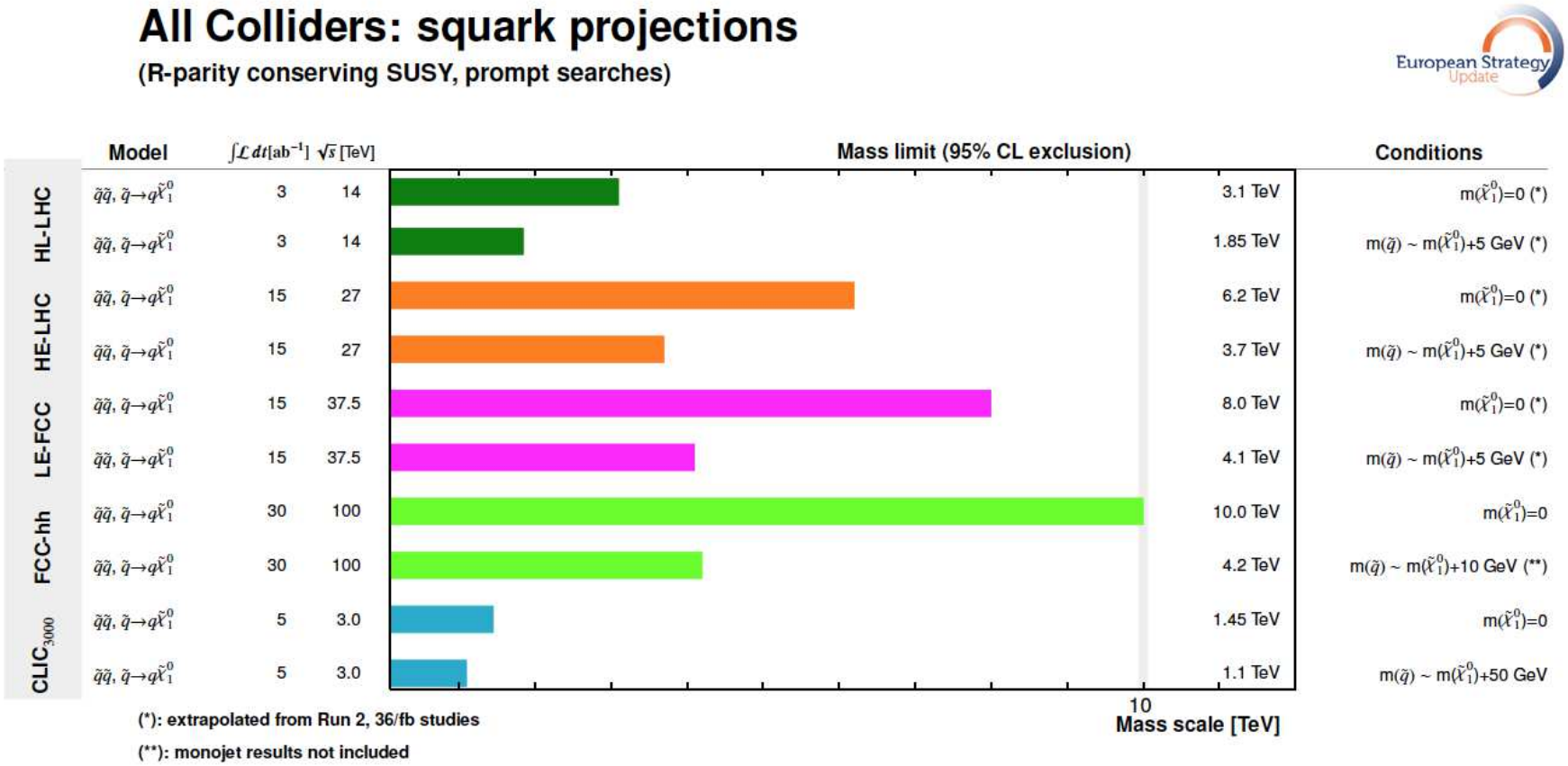
# Future reach for gluinos in RPC SUSY




⇒ simple message: energy wins

⇒ analysis with RPV SUSY missing . . .

# Future reach for scalar quarks in RPC SUSY

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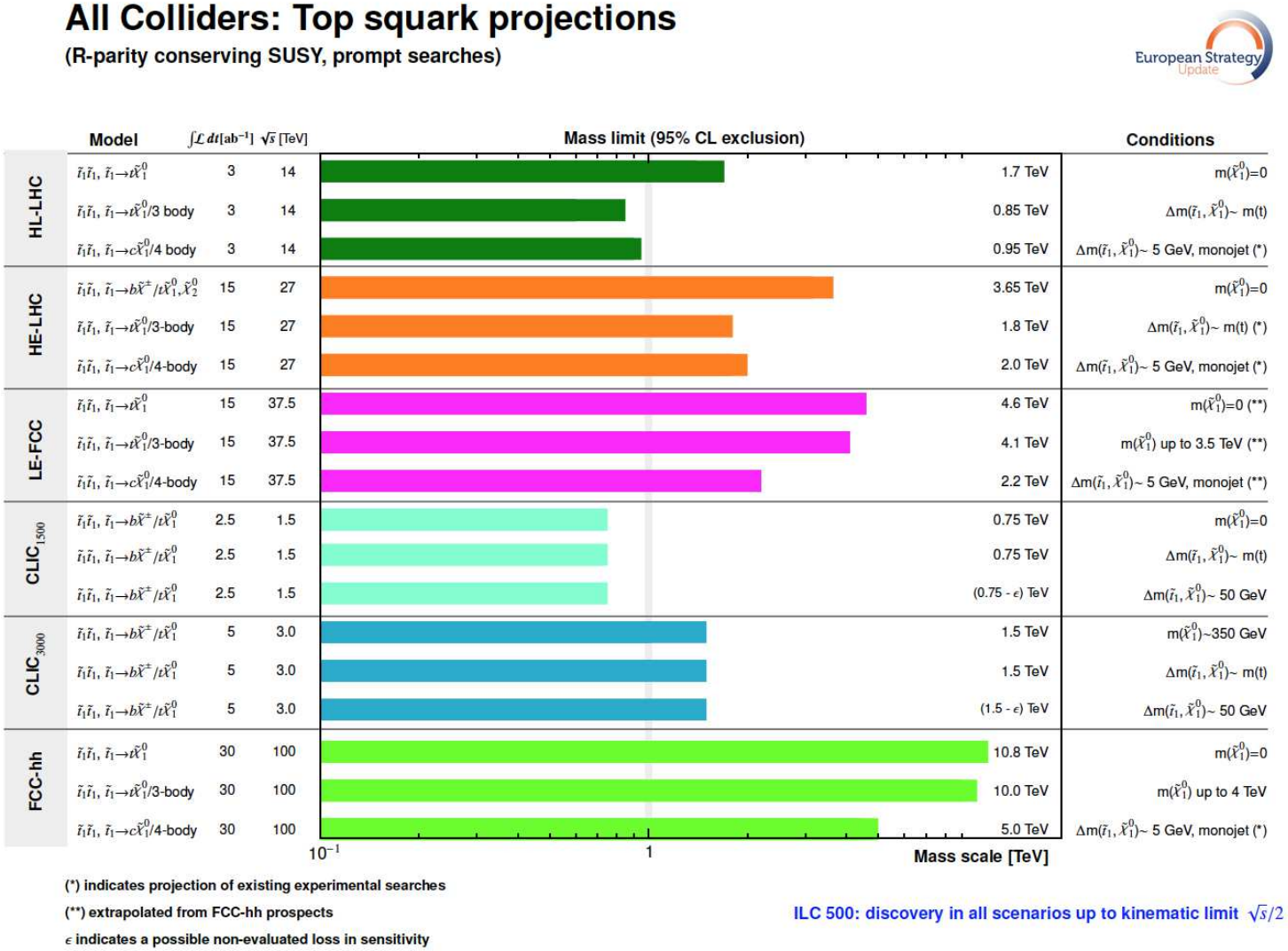
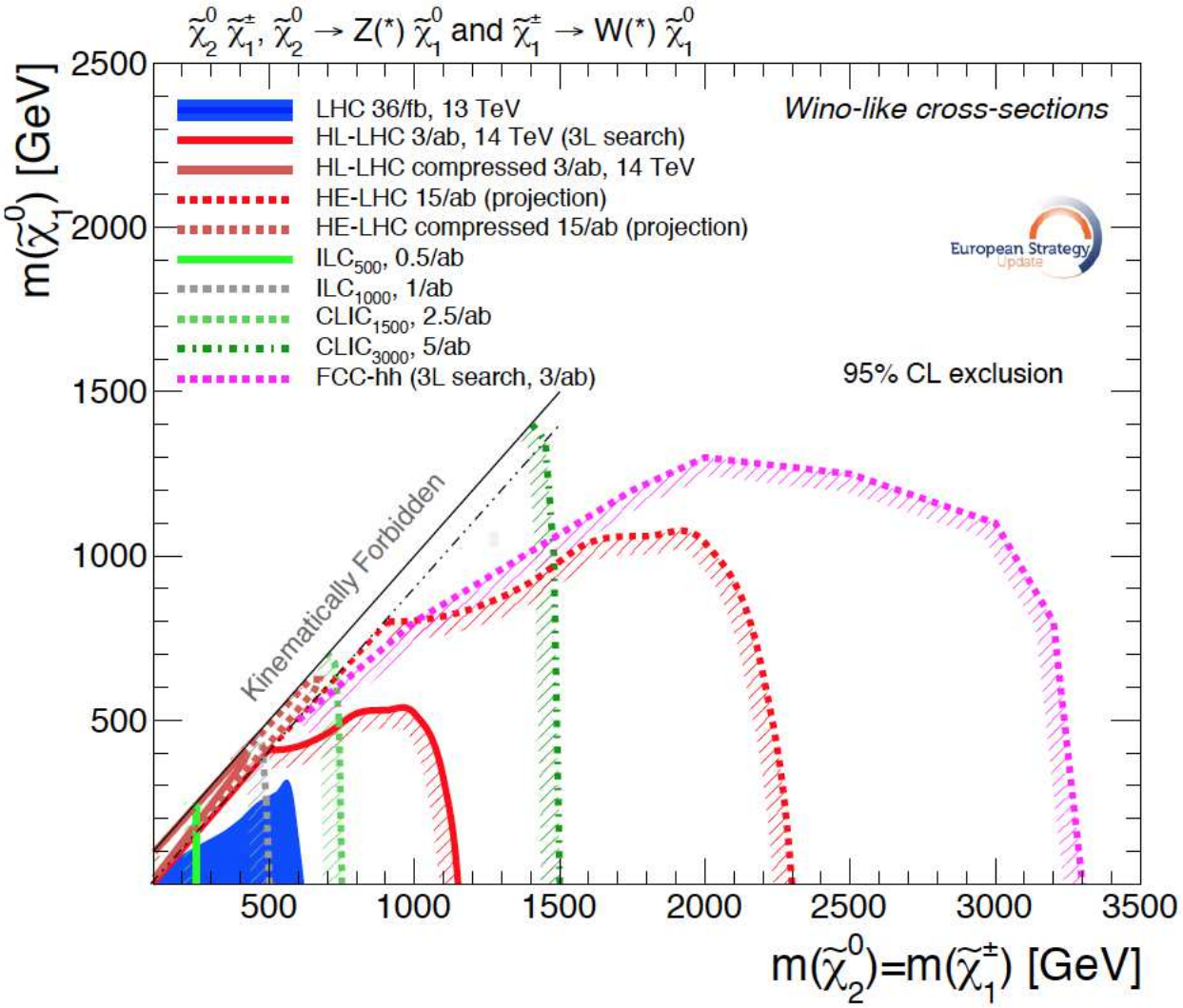
# Future reach for scalar tops in RPC SUSY




$\Rightarrow$ simple message: energy wins

$\Rightarrow$ "complicated" regions? $\Rightarrow e^+e^-$ advantages

# Future reach in the golden chargino/neutralino channel

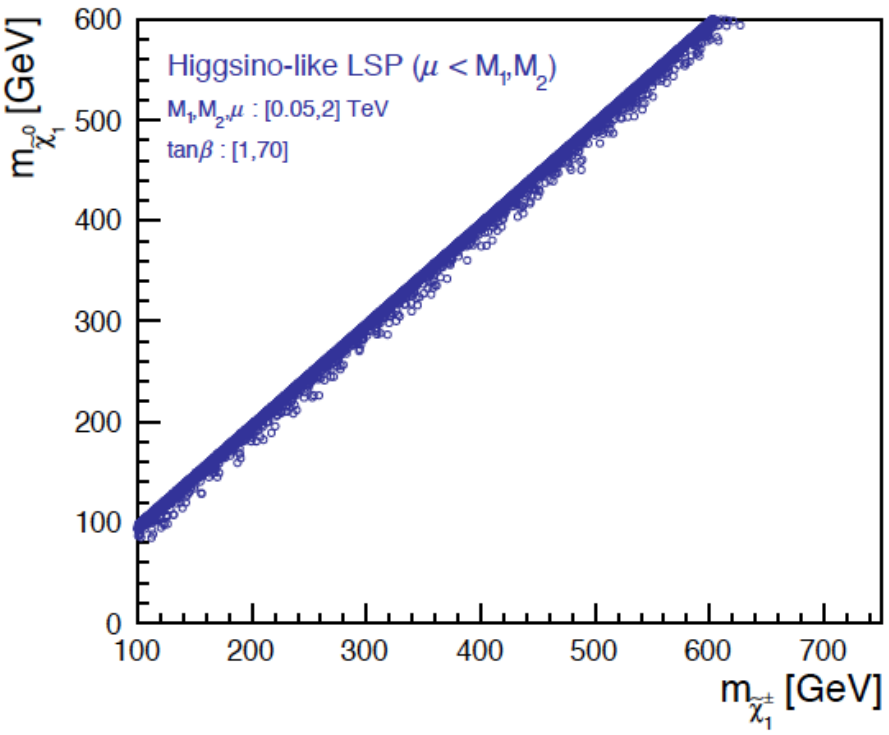



$\Rightarrow$ clear complementarity between $pp$ and $e^+e^-$

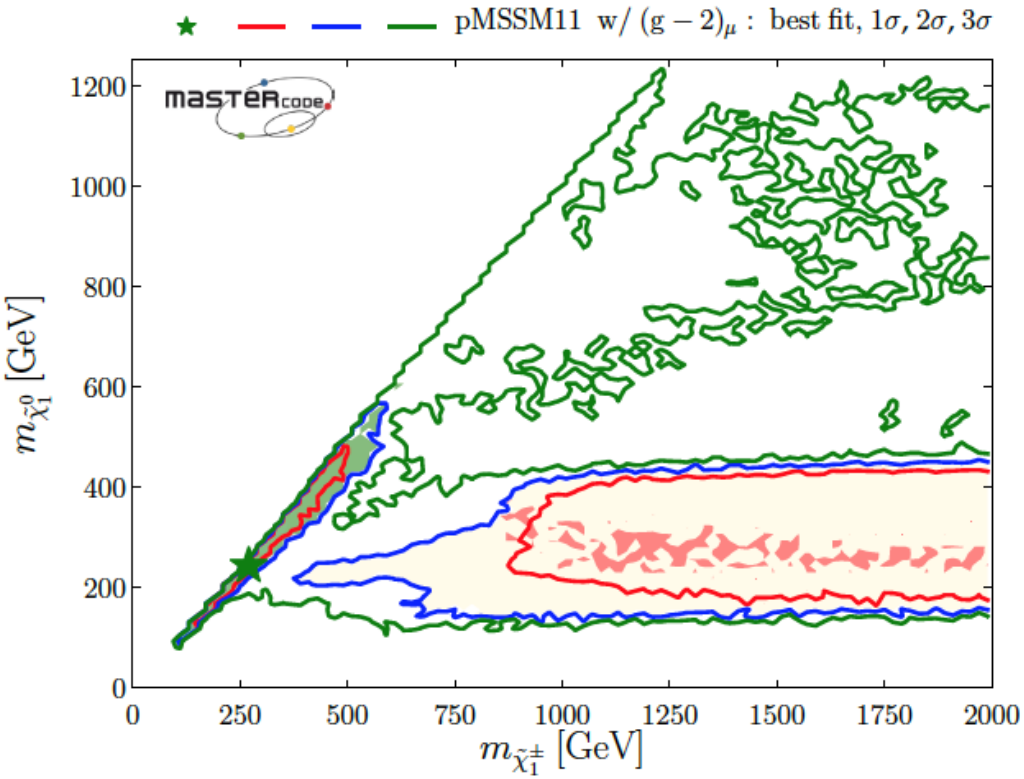
$\Rightarrow$ How relevant are compressed spectra?

# How relevant are compressed spectra?

## Natural SUSY: low $\mu$



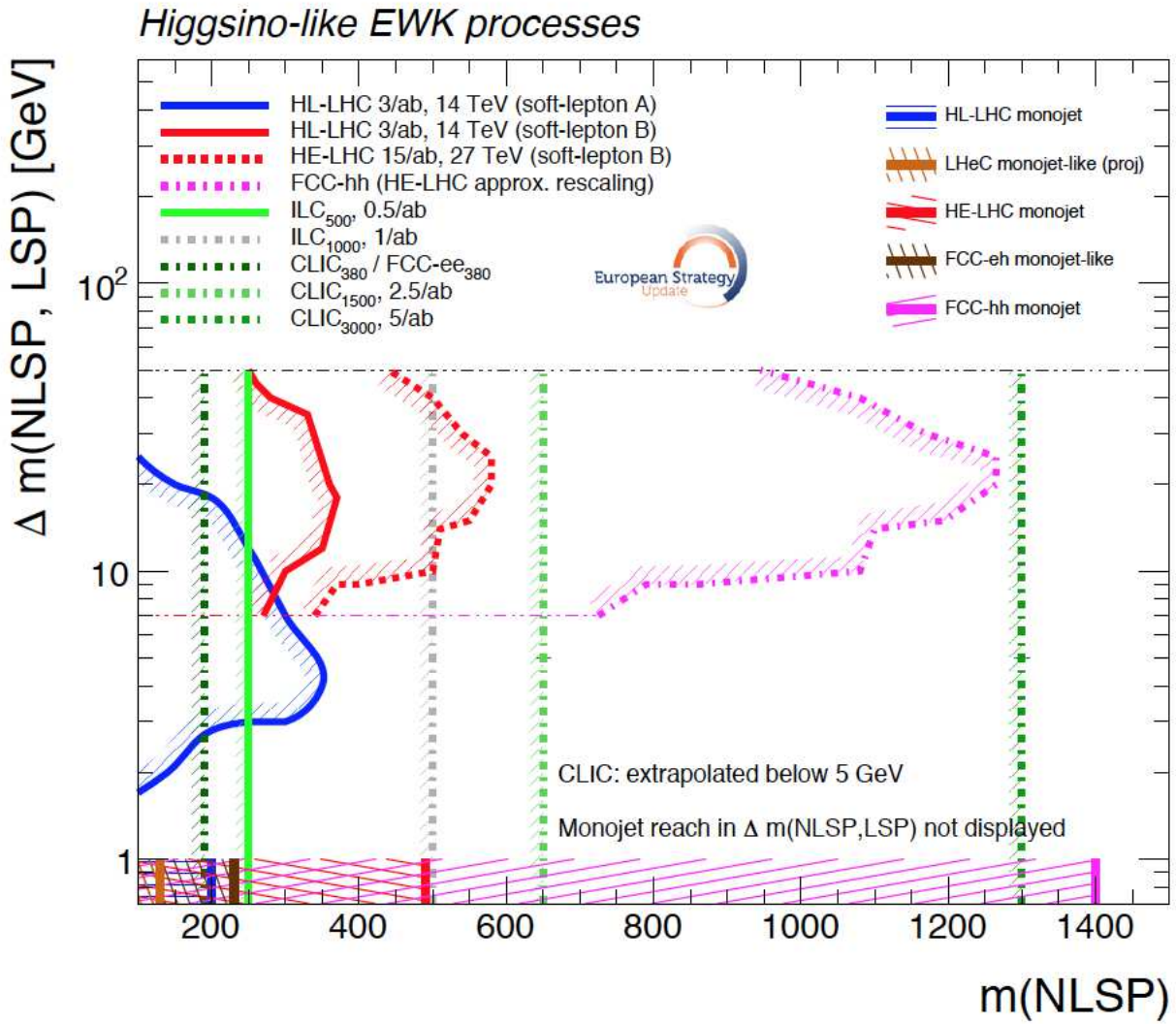

## Global pMSSM11 fit




$\Rightarrow$ two well motivated and independent scenarios

$\Rightarrow$ both favor independently compressed spectra

# Future reach for compressed spectra




$\Rightarrow$ clear complementarity between $pp$ and $e^+e^-$

$\Rightarrow$ $e^+e^-$ much more "robust"!

# 5. Conclusions

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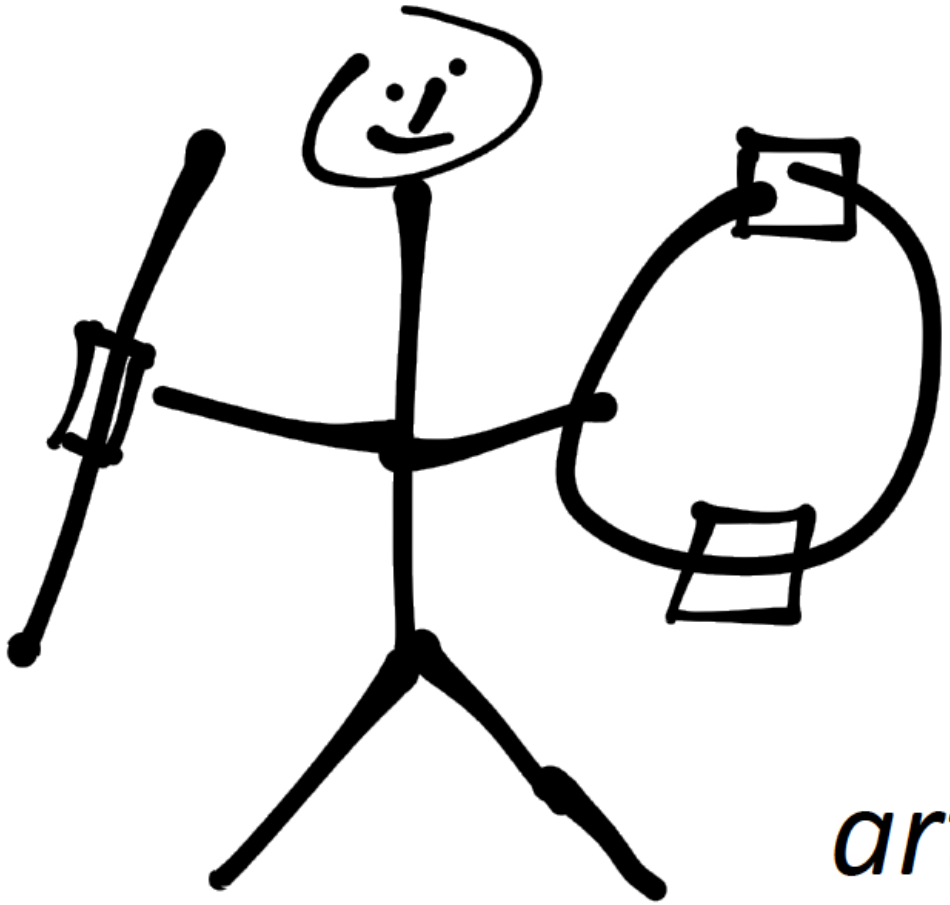
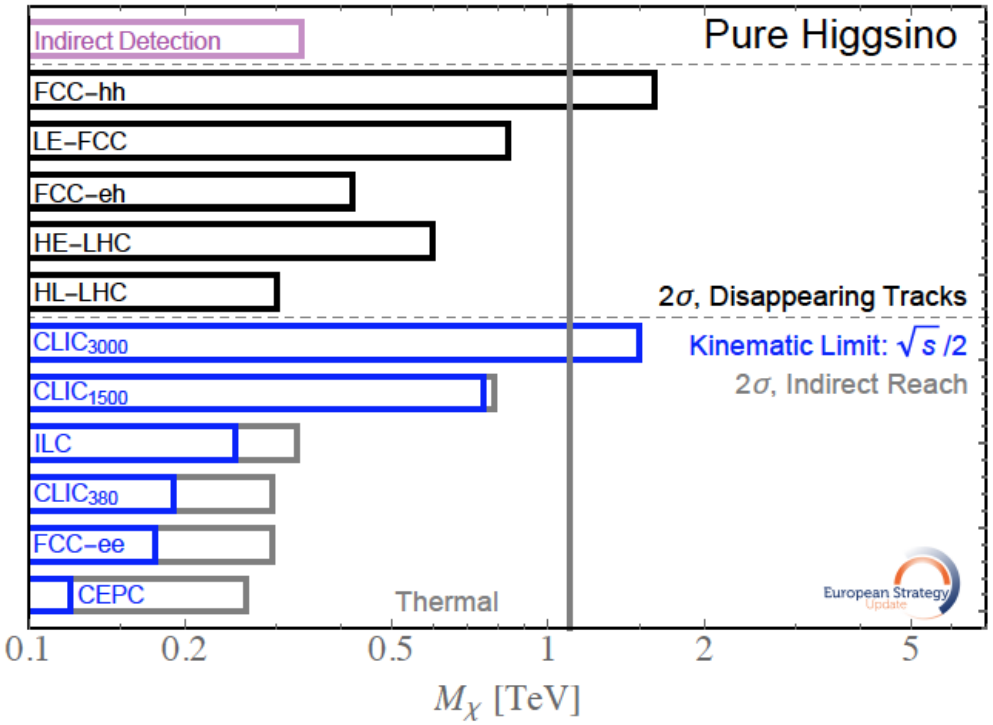
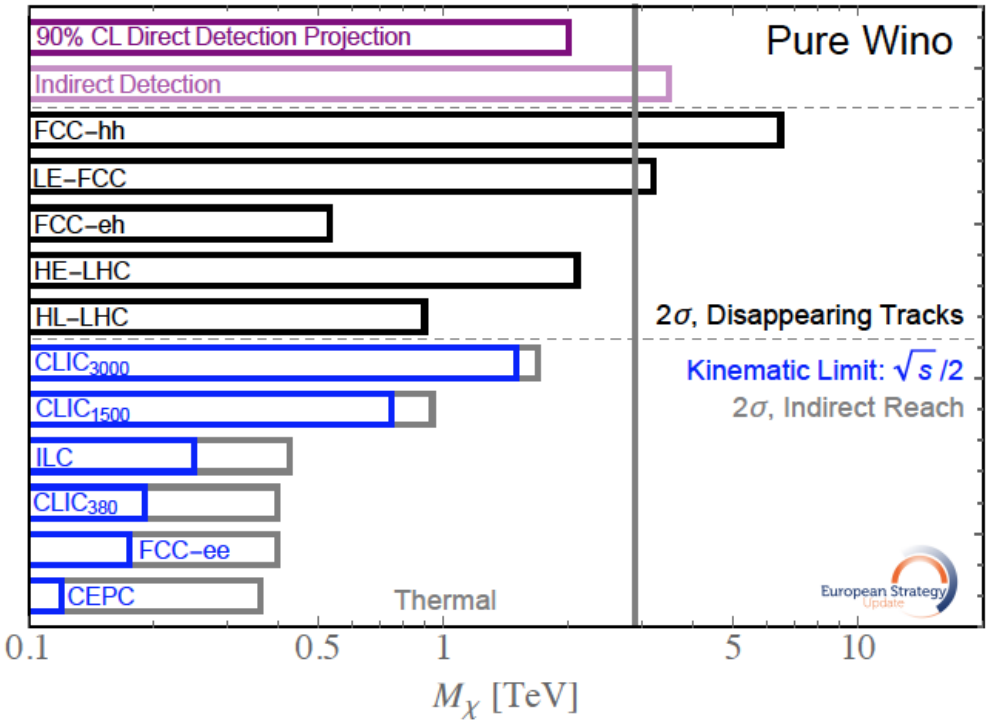


*artwork by F. Simon*


Further Questions?

# Future expectations: direct DM reach




⇒